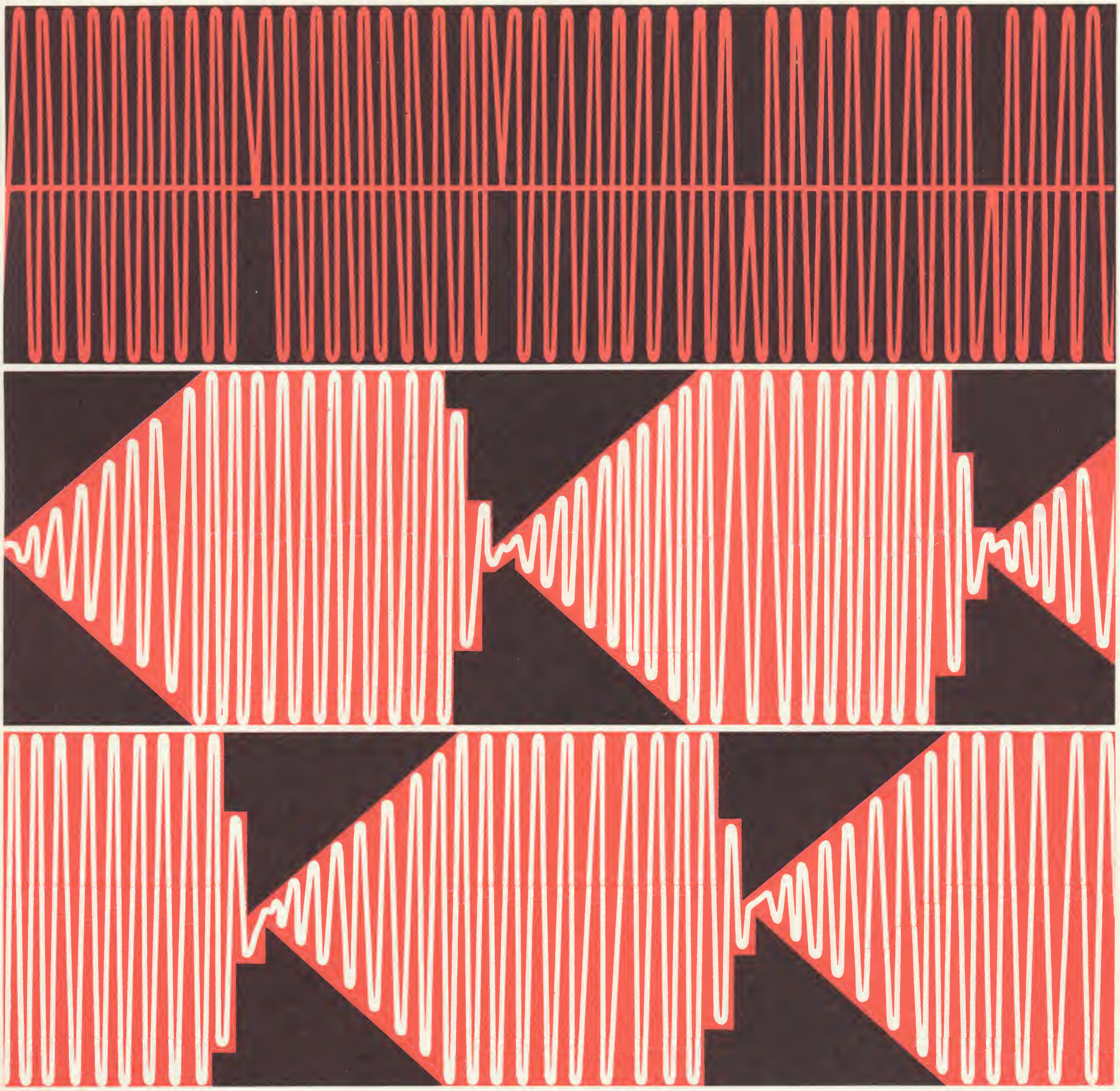
Collins High Speed Data Transmission System Kineplex®

COLLINS



Research and Development

Digital data transmission is rapidly achieving a significance equal to that of voice transmission.

One of the major factors accounting for the growth of digital communications is the evolution of the computer with its almost limitless potential for information processing. Practical and efficient exploitation of this potential demands extremely fast and accurate means of moving data between processors and between processors and remote stations.

Evidence of the progress already made in transmission techniques is seen in the fact that data speeds of millions of words per minute are now possible.

Much of the technology upon which this capability is built was developed in the laboratories of Collins Radio Company.

MORE EFFICIENT SYSTEMS

One of the first needs for more efficient high speed digital data communication systems became evident in military applications following World War II. An increased requirement for world-wide radio communication, coupled with limitations on the availability of usable spectrum, prompted an interest in more efficient digital communication systems.

The advent of tactical operation systems, radar data networks and command and control systems presented many requirements for digital transmission rates up to 2400 bits per second. The 2400-bit rate is, in contrast, 32 times the rate of the 100 wpm (75 bits per second) teletypewriter circuit.

One of the answers to this need lay in an extensive research and development program which Collins started on digital data transmission systems in the 1940's. A major objective of the program was the development of digital signalling detection techniques for faster and more accurate data transmission, and for more efficient use of the communication channel bandwidth on radio and wireline circuits.

PREDICTED WAVE SIGNALLING BY COLLINS

Data transmission equipment placed in service in the mid-1940's had demonstrated the relative advantages of frequency shift keying (FSK) over on-off keying. A study of FSK, however, indicated that much better signal-to-noise performance was possible than was being achieved. It was clear that improved frequency stability, better signal integration and synchronization were techniques that would not only improve signal-to-noise performance but at the same time provide better utilization of bandwidth.

A major achievement of Collins' program was the development of predicted wave signalling, a synchronous modulation-detection technique which incorporated quadrature phase shift keying (PSK) and coherent detection. The technique incorporated kinematic filtering and signal multiplexing and, therefore, was named Kineplex. The Collins Kineplex data transmission modem (modulator-demodulator) equipment was the first equipment of its kind to be placed into service employing this new technology—*the modem technology which is now universally accepted as that which provides minimum error rate with maximum transmission rate per unit of bandwidth.*

Kineplex modem equipment permitted transmission rates of more than twice those of the non-synchronous FSK signalling. It also permitted signal-to-noise improvements of 6 to 8 db.

NEW DIMENSION IN REQUIREMENTS

A new dimension to digital data communication requirements has developed with the rapid advance of computer technology. Establishment of data processing centers with large data handling capabilities has emphasized the need for effective and efficient means of gathering and disseminating data between geographically separated locations. The trend toward more powerful and efficient data processors has led to a requirement for greater data speeds and accuracy between data processors and the sources that generate and use the data. Data communications is a significant factor in the ultimate efficiency attainable with any large integrated processing system.

Data transmission requirements will continue to place a premium on speed and accuracy of transmission and upon efficient utilization of communication channel bandwidths. Requirements of transmission speeds will generally range from a few hundred to several hundred thousand bits per second.

The range of higher transmission speeds will require communication channels having proportionally wide bandwidths. Whereas to date the voice bandwidth channel has been the channel used most widely for data transmission, wider channels of 48 and 240 kc are now available on common carrier networks. The relatively lower cost for the wide bandwidth channel makes the channel attractive for high speed data transmission requirements.

CONTINUING RESEARCH

Collins' continuing research and development in the area of data communication has been directed toward providing data transmission equipment designed to satisfy a wide range of new requirements.

Later generations of Kineplex modems have provided major improvements in data speed per unit of bandwidth and higher data service over channel bandwidths from voice to wideband. Nominal data speed capabilities over wireline facilities are from 4800 bits per second through a voice channel to 240,000 bits or more per second through a 240 kc channel. These capabilities represent a 100 per cent increase in transmission rate per unit of bandwidth.

The increased speed performance is accompanied by high order modulation using differentially detected AM modulation. Addition of a single level of modulation to the quadrature phase modulated data tone gives a 50 per cent increase in data speed with no decrease in the transmitted pulse length.

EQUIPMENT COMPILER SYSTEM

New Kineplex modems make use of a computer design release system called ECS (Equipment Compiler System). ECS provides a flexibility which permits selection of such parameters as number of tones, tone frequency, keying rates, and mechanical configurations. Such a selection enables the user to optimize modem performance for the expected communication channel characteristics and system requirements.

With ECS, complete manufacturing releases are made in less than two weeks after receipt of customer's requirements.

ADAPTIVE

Collins' new modems have the capability of adaptive control. Provision is made to turn tones on and off, to add or delete amplitude modulation and to change output level from a remote digital source.

The modems employ integrated circuits for all logic functions. Construction is compact with rack, drawer or ATR packaging options available. Diversity operation, integral test facility and a high stability of 1×10^{-8} per day frequency standard are available optional features.

Standard modem configurations for wireline service provide 4800 bits per second on common carrier voice channels having characteristics as defined by Schedule 4B in FCC Tariff 237.

Standard configurations are also provided for HF radio circuits, and for communication over broadband channels.

In short, the new Kineplex modems provide an efficient, high speed capability for all of today's data transmission requirements.

Theory and Operation

There are many modulating and demodulating techniques for transmitting data. The basic "ON-OFF" (amplitude modulation) technique using a single frequency is quite simple. A carrier signal is turned "ON" for a MARK condition and turned "OFF" for a SPACE Condition. The detector is usually an amplitude threshold measuring device. The setting of the threshold level becomes a very difficult engineering problem because of noise and signal variation problems.

As the state of the art improved, an attempt was made to alleviate the threshold setting problem. Frequency Shift Keying was implemented in such a manner that when the MARK frequency was transmitted, the receiver could compare the detected output of two filters. The detector would look at two filter outputs and pick the greater of the two. Early FSK systems were wideband, with a frequency shift of ±425 cps from a center frequency. Narrow band FSK systems with a frequency shift of ± 42.5 cps around a center frequency followed in an attempt to conserve bandwidth. The next step was to synchronously transmit and synchronously detect the information by use of narrow band filters.

The last step was to further reduce the bandwidth requirements and conserve frequency spectrum. AMPLITUDE and FREQUENCY had been exploited and the only remaining controllable parameter was PHASE. By considering phase shifted modulation techniques, a single frequency was used for transmitting the information with the MARK and SPACE encoded as different phases. This yielded a 2 to 1 savings in required bandwidth over the narrow band FSK. Additional bandwidth conservation was achieved by sending more than one bit of information on a given tone by the use of phase multiplexing.

PHASE MULTIPLEXING

Phase Multiplexing is a technique where two or more binary data channels cause the phase of a signal to be shifted in predetermined amounts depending upon the data content of the channels involved.

The signal source at the transmitter is a constant amplitude sine wave of high stability. With the aid of Figure 1, it will be shown how two data sub-channels are phase-multiplexed on a single audio tone. Figure 1 is a vector diagram representing the phase of the audio tone for the duration of one transmitted element. Sub-channel X is shown as the horizontal axis

passing through 0° and 180°, and sub-channel Y is the vertical axis passing through 90° and 270°.

When the input to sub-channel X is a MARK, the phase of the audio tone is maintained at zero degrees, and when it is a SPACE the audio tone is phase shifted by 180°. Moreover, sub-channel Y independently phase shifts the audio tone 90° for a MARK input and 270° for a SPACE input. The phase-shifted tone from sub-channel X is then vectorially added to the phase shifted tone from sub-channel Y. This vector addition yields a constant amplitude audio tone which has a phase vector according to the MARK-SPACE coding of two input sub-channels.

As an example, a MARK input from sub-channel X (M_X) and a MARK input from sub-channel Y (M_Y) causes the phase of the output to shift 45° for the duration of one transmitted element. The four quadrature phase combinations are shown in Figure 1 and are as follows: $M_XM_Y = 45°$ $S_XM_Y = 135°$ $S_XS_Y = 225°$ $M_XS_Y = 315°$

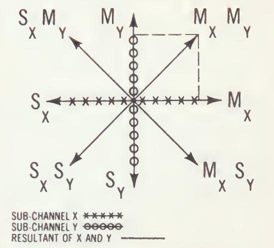


FIGURE 1 PHASE CODING OF TWO BINARY SUB-CHANNELS ON ONE TONE

It is assumed that the phase is changed rapidly in a synchronous manner and that the length of the vector and its relative phase is constant during each transmitted element period. It is evident that simple circuitry can be used in the transmitter to generate the desired frequencies which are only shifted in phase with respect to each other.

ENERGY – FREQUENCY DISTRIBUTION:

A signal of constant frequency, integrated over a period T in seconds as a function of frequency ($f = 1/T$) will vary as illustrated in Figure 2. This shows that at a frequency removed $1/T$ from the signal frequency, the integrated signal energy is zero. It would be confusing to try to visualize a transmitted signal of the type considered in terms of carrier and sidebands. This energy versus frequency relation should be kept in mind.

Predicted wave detection, as employed in Kineplex, makes use of a weighting function for the square wave in the form of an infinite Q resonator gated in synchronism. This resonator provides integration over the length of the pulse.

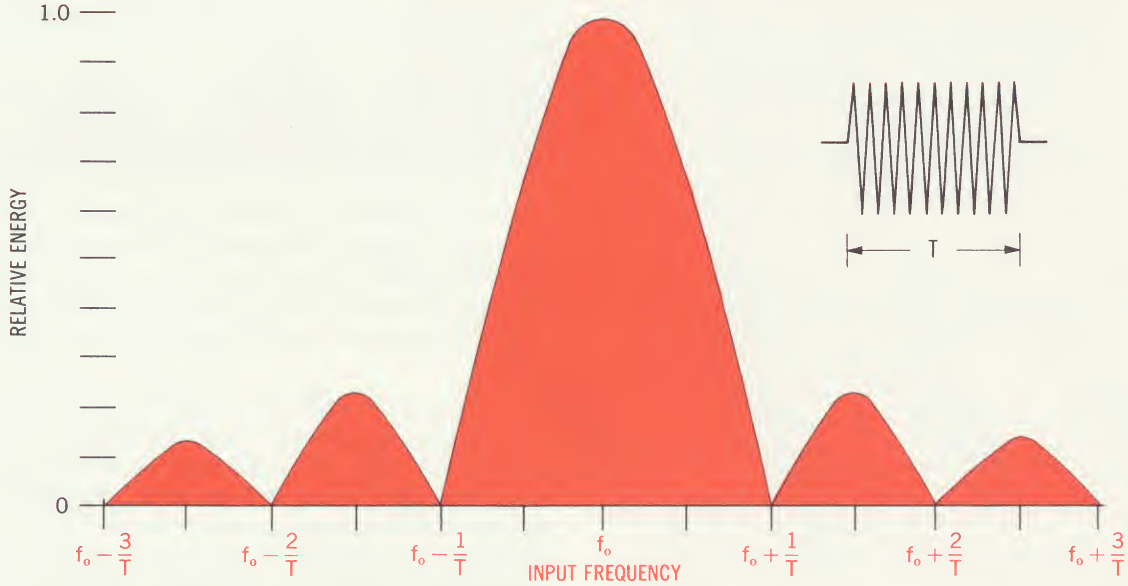


FIGURE 2 ENERGY VS FREQUENCY RELATIONSHIP OF A TRANSMITTED PULSE

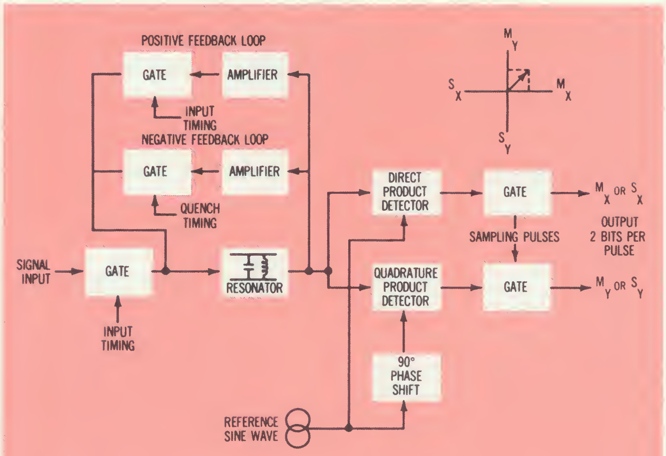


FIGURE 3A COHERENT DETECTION SCHEME

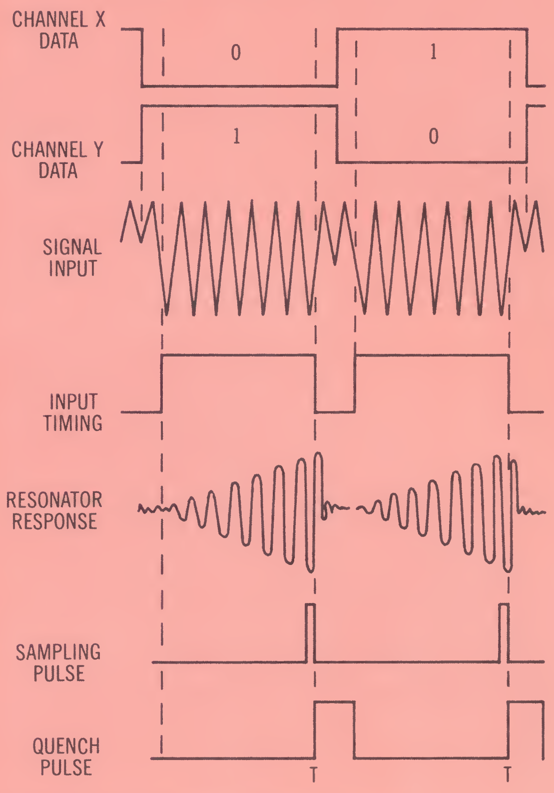


FIGURE 3B DETECTION WAVEFORMS

COHERENT DETECTION

Coherent detection is based on predicting the nature and characteristics of the signal to be received and correlating it with some locally available reference signal.

Figure 3 shows the various timing gates and signal conditions throughout the receiving circuitry. When a signal is expected from the transmitter, the input timing gate opens and the input signal is applied to the resonator-amplifier along with the positive feedback signal.

During the time that this positive feedback is gated around the resonator and amplifier, the circuit is regenerative just to the point of oscillation. Under this condition, the resonator will appear to have infinite Q.

For the time interval that the signal is applied to the resonator, the oscillations build up linearly since effectively no energy is dissipated in a resonator that has infinite Q. This is shown on the RESONATOR RESPONSE waveform in Figure 3B. The resonator is an electromechanical transducer with a Q of approximately 1000. It is constructed to resonate at the frequency generated in the transmit section.

The output of the resonator is fed to two phase detectors. The phase detector outputs are sampled at the end of the integration time (T) by the sampling pulse. The signal will have been integrated to provide a maximum signal-to-noise ratio.

When the negative feedback is gated around the resonator-amplifier and the positive feedback is gated closed, the oscillation in the resonator will be completely damped. The resonator is then ready to receive the next signal pulse.

Figure 3 assumes that a perfect phase reference is present at the receiver. Such an arrangement is referred to as a Coherent Detection Scheme. The reference sine wave is coupled into one phase detector to provide its reference voltage and is shifted 90 degrees in phase and applied to a second phase detector.

The outputs of these two phase detectors at the time of sampling gives the indicated projection of the received signal on the X and Y axes. In this manner, the output of the phase detector for the "X" sub-channel will be positive when the signal in that sub-channel is a MARK, binary one (1), and will be negative for a SPACE, binary zero (0). Similarly the output of the other phase detector will indicate whether the signal in the "Y" sub-channel is a MARK (1) or a SPACE (0). Accordingly, two bits of information per signal are obtained.

FREQUENCY MULTIPLEXING

An important consideration is the bandwidth required for each predicted wave sub-channel. If T equals the time duration of each pulse, the bandwidth (BW) required per sub-channel is equal to 1/T. To prove that BW = 1/T, it must be shown that the sub-channels may be arranged in a frequency multiplex system spaced 1/T cycles apart in successive frequency intervals without crosstalk. If this is shown, the effective BW per sub-channel may be regarded as 1/T. Demonstration of the freedom from crosstalk is possible by reference to the energy-frequency diagram of the pulse and by examination of the response of the gated resonator as its frequency is varied. See Figure 4.

The upper curve in Figure 4, is the energy vs. frequency distribution of the transmitted signal which appeared in Figure 2.

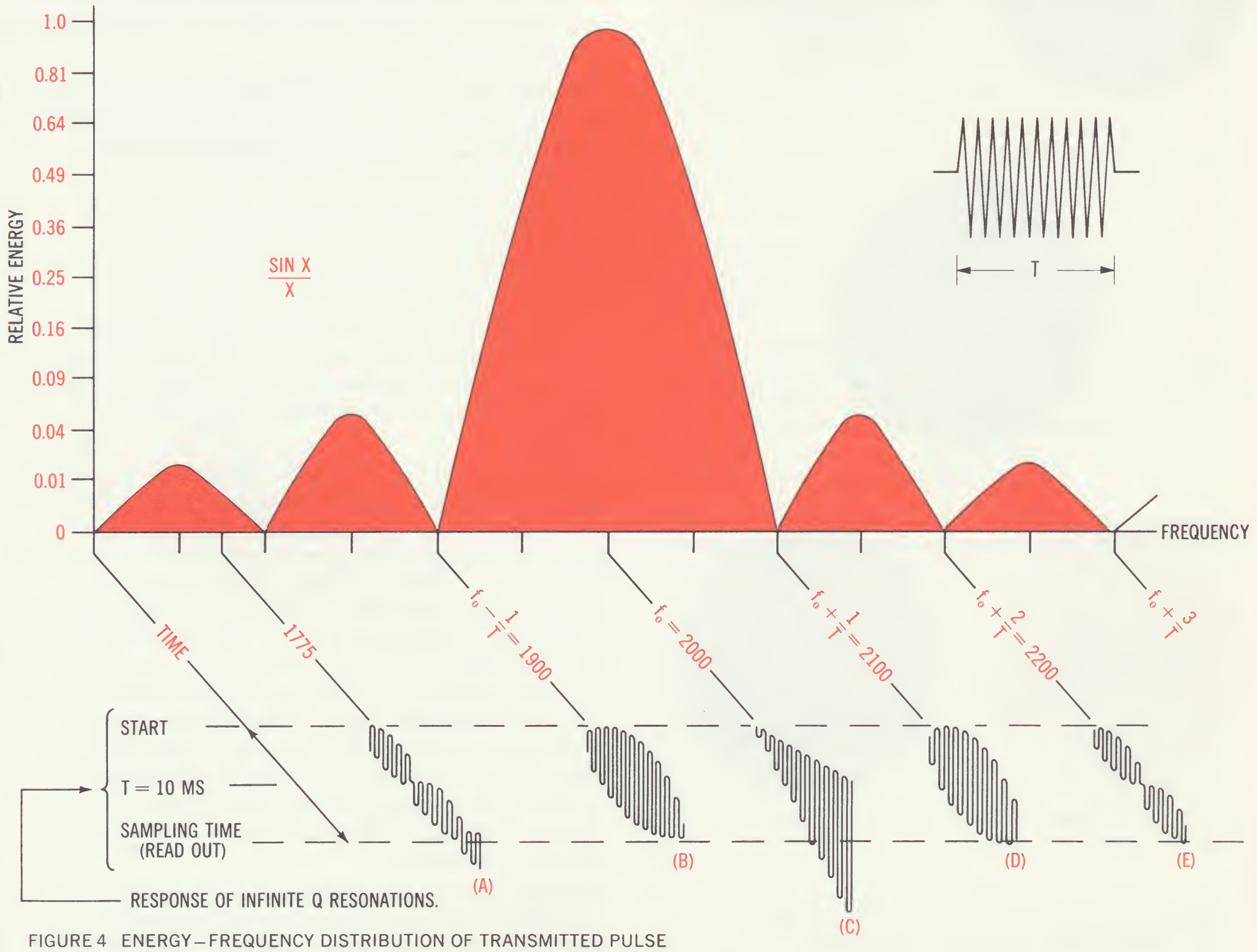


FIGURE 4 ENERGY–FREQUENCY DISTRIBUTION OF TRANSMITTED PULSE

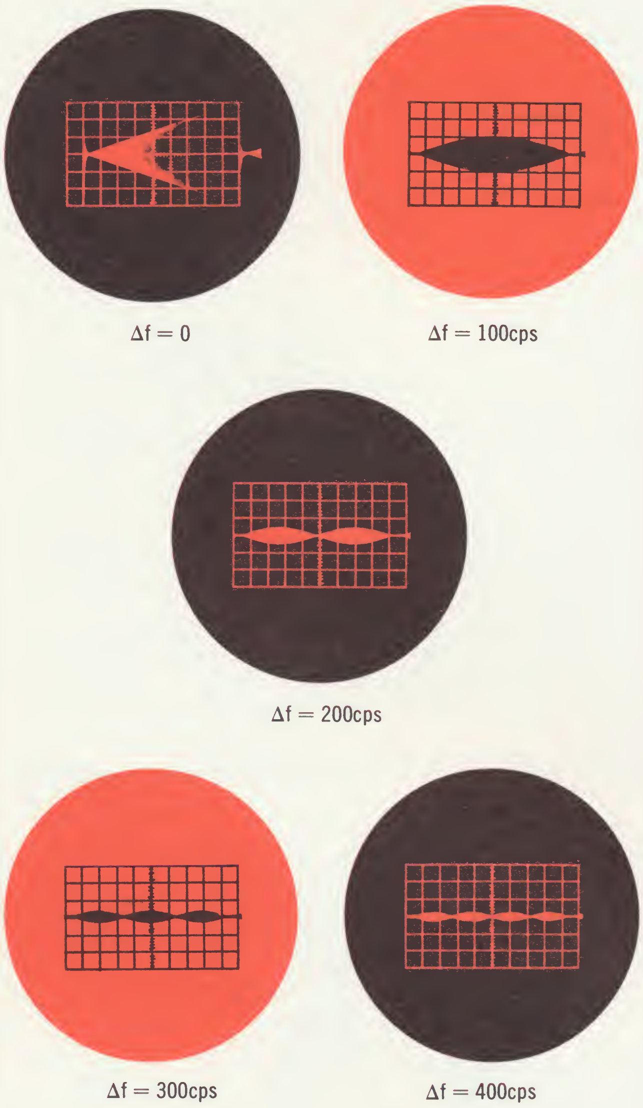


FIGURE 5 RESPONSE OF THE GATED RESONATOR (KEYED FILTER) WITH 10MS GATE. Δf = DIFFERENCE BETWEEN SIGNAL AND RESONATOR CENTER FREQUENCIES.

To provide a numerical example, the center frequency is shown as 2000 cps.

Also, for illustration, the 2000 cps pulse is indicated as being 1/100 second in duration giving $1/T = 100$ cps. At f_o the amplitude response of the resonator at the desired frequency, 2000 cps, is indicated. It will be observed that the resonator amplitude builds up linearly to the sampling (readout) time (Figure 4c.)

During the 2000 cps pulse time, resonators which are tuned to 1900 cps and 2100 cps ($f_o \mp \frac{1}{T}$) provide the responses shown in Figure 4b and 4d.

The amplitude first builds up and then decreases to zero at readout. (Note that the upper curve which represents the energy distribution of the 2000 cps pulse has a null or orthogonality at each of these frequencies.)

A similar result, namely zero output at readout time, is obtained at 2200 cps, except that at this frequency the resonator frequency is displaced and its amplitude goes through two maxima and two zeros (Figure 4e.)

Corresponding results will be obtained if the resonator frequency is displaced by additional 100 cycle increments with the number of maxima and number of zeros corresponding to the number of such increments the frequency is displaced.

The curve for 1775 cps (Figure 4a) indicates the response of a resonator which is not accurately centered at $f_o - 2/T$. There is a residual voltage at sampling time corresponding to the energy distribution indicated on the upper curve. Of interest is the response of a resonator when both the desired and adjacent sub-channel signals are transmitted. The output at sample time will be the same as it would be if the desired sub-channel had been transmitted alone. However, during the pulse interval the resonator stored energy will vary as the vector addition of the signals for the sub-channels taken individually. Similarly, if there are a large number of sub-channels operating at once, the resonator will respond in a complex fashion during the pulse, but at sampling time will reach a value corresponding to the correct value for the desired channel alone.

Figure 5 is a series of five oscillograms showing actual resonator responses corresponding to the conditions examined in the previous figure. Each oscillogram was taken with the same resonator input power and oscilloscope

sensitivity. The decrease in maximum stored energy in the resonator with increase in Δf is demonstrated.

A three dimensional view of the gated resonator (Keyed filter) response showing the relationship of Amplitude vs. Frequency and Amplitude vs. Time appears in figure 6. The oscillograms depicted in Figure 5 can also be seen in that part of Figure 6 which illustrates the plot of Amplitude vs. Time.

The $\frac{\text{SIN X}}{\text{X}}$ curve which was shown earlier can be seen in Figure 6 as the plot of Amplitude vs. Frequency.

PREDICTED WAVE DETECTION AND SIGNALLING

Before showing this practical arrangement as it is incorporated in Kineplex a few of the prominent features of the system will be considered.

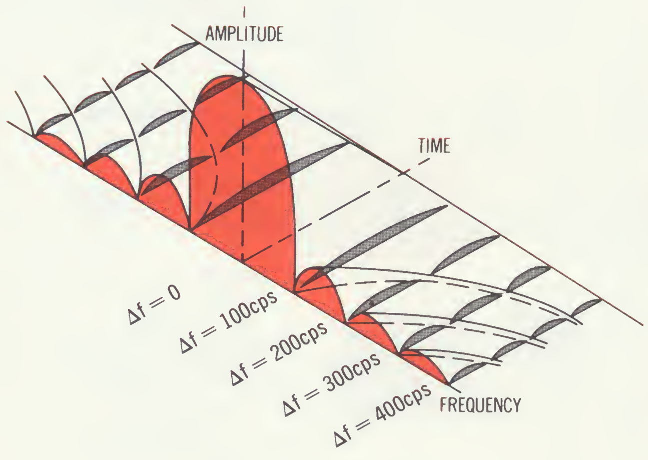


FIGURE 6 "THREE DIMENSIONAL" GATED RESONATOR (KEYED FILTER) RESPONSE SHOWING RELATIONSHIP OF AMPLITUDE, TIME AND FREQUENCY.

1. Although a frequency multiplex arrangement was used to demonstrate that BW = 1/T, the performance is basically identical with either time or frequency division. Signal-to-noise ratio performance of a single channel is the same whether flanking channels are present or not.

2. It is permissible to restrict the band emission of the transmitter by filtering to eliminate the side energy beyond about ± 3/T. The amount of energy contained in the signal beyond this third orthogonality is so small that it can be filtered out with small effect on operation. This feature is of importance in limiting intersystem interference.

3. Adjustment of resonator feedback for "infinite" Q is not critical because of the initial high Q resonator. Normal circuit tolerances are sufficient.

4. It should be noted that receiver selectivity is basically determined by the gated resonator with additional IF and RF selectivity being required only for strong signal protection.

5. Predicted wave detection yields a gain in signal-to-noise ratio performance accompanied by a *lowering* of the threshold and a *narrowing* of the band. This is in marked contrast to the usual result in systems such as FM where a gain in signal-to-noise ratio performance is attained only by *raising* the threshold and *widening* the band.

An important difficulty in applying the laboratory system just described to practical transmission links, is that of maintaining a reference wave in exact phase synchronism with the transmitter reference and adjusting for variations in phase delay which occur in the medium. These variations in phase stability are due to DOPPLER and MULTIPATH effects, layer height changes, etc. One solution would be to transmit a pilot reference signal of low relative power, clean it up by filtering or AFC methods and then establish a local reference. The question arises, however, whether the pilot channel would suffer the same disturbances as the signal channels. Because of this uncertainty and to simplify the system, it is more convenient to use each period as a reference for the following period. (Differential Phase Detection). This procedure is a good engineering solution because a period may be selected such that the phase changes expected in the medium will be small over one period and, hence, will be nearly correct for analysis of the following period.

DIFFERENTIALLY COHERENT PSK SYSTEM

The predicted wave signalling detection system incorporated in the Kineplex System is shown in Figures 7A and 7B. This system has the following basic features:

1. Information is encoded as the vectorial addition of two quadrature components.

2. Two resonators are used alternately at the detector. Each resonator is permitted to "ring" for one period as a means of storing a phase reference for analysis of the following period (differential phase comparison). It is then quenched and re-used.

3. Phase measurements so obtained are decoded by phase detectors arranged to interpret the phase difference from period to period as originally encoded.

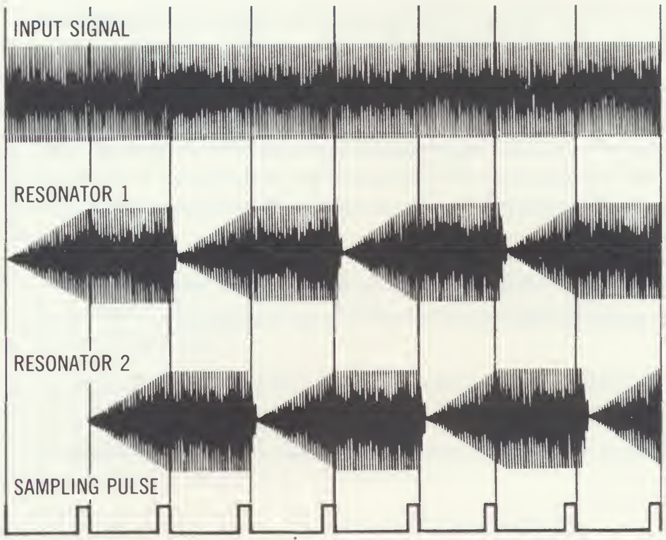


FIGURE 7A MATCHED FILTER DETECTION WAVE FORMS

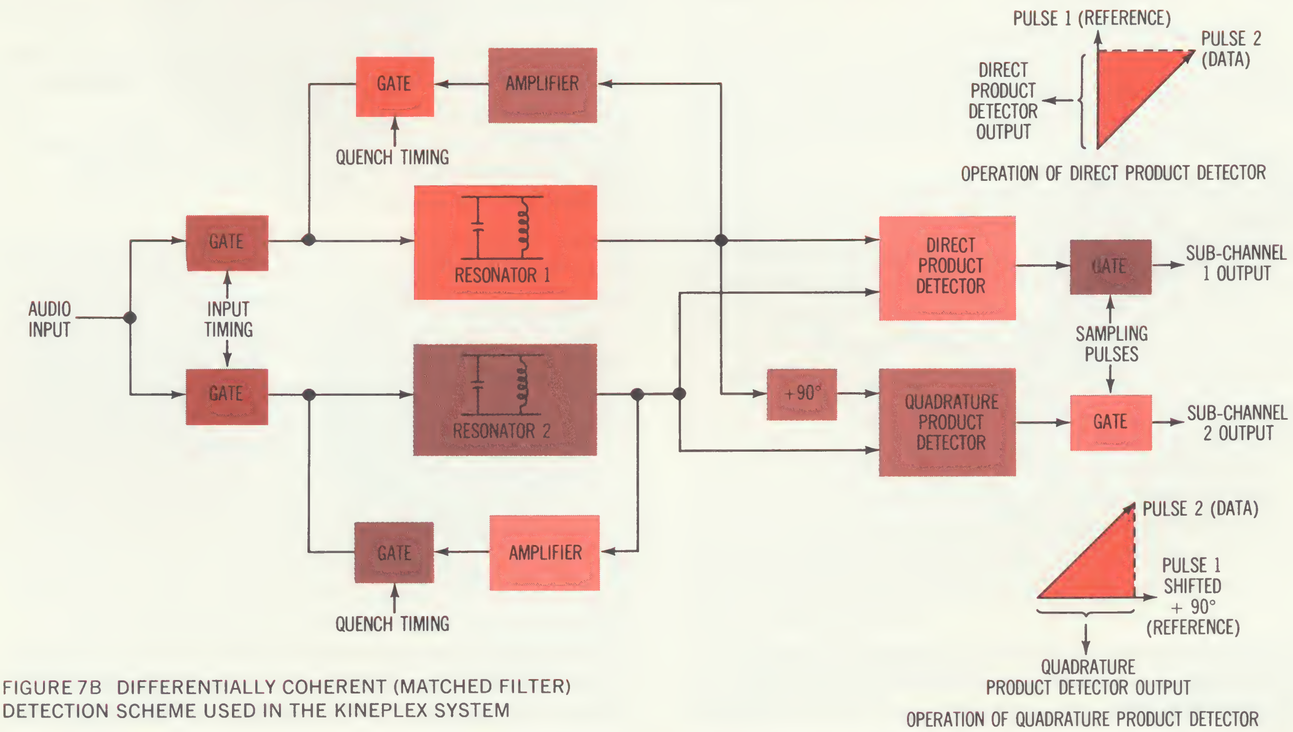


FIGURE 7B DIFFERENTIALLY COHERENT (MATCHED FILTER) DETECTION SCHEME USED IN THE KINEPLEX SYSTEM

PHASE MULTIPLEXING WITH AMPLITUDE MODULATION (AM)

As discussed earlier, the sub-carrier data tone experiences prescribed phase shifts at the beginning of each data frame. By imposing both AMPLITUDE and PHASE SHIFT MODULATION on the data tone in accordance with the logic levels of three binary data channels, the data rate is increased an additional 50%. The Amplitude Modulation is differentially detected, i.e., the amplitude of the preceding frame is used as a reference to determine the binary data.

For any given data frame, the data tone amplitude assumes one of two levels (100% or 40%) depending on the logic level of the third binary data channel. Whether 100% Amplitude is to represent MARK or SPACE data is arbitrary and may be tailored to each customer's requirement.

The customary two channels of binary data for a phase shift keying system may thus be increased to three channels per tone by amplitude modulating the sub-carrier frequency tone as shown in Figure 8. At the top of Figure 8, the amplitude of the phase shifted sub-carrier tone can be seen. For the first frame, maximum amplitude of the carrier is shown. This will be detected in the receiver as MARK data on the third channel. In the second frame, the amplitude has been reduced to 40% of full amplitude. This is detected as SPACE data.

The detection of binary data on the third channel in the receiver is accomplished by comparing the relative amplitude of the two matched filters (Keyed Filter A and Keyed Filter B) in the AM Data Detector.

To detect the binary data on the third channel, two successive AM information bits are required. One information bit is referred to as the variable or UNKNOWN voltage and the other as the REFERENCE voltage. The UNKNOWN voltage is the amplitude of one of the matched filters at the end of the integration period. The REFERENCE voltage is the amplitude of the other matched filter which was allowed to ring for one frame time.

The "transfer function" for the AM Detector is such that the UNKNOWN voltage is compared against the REFERENCE voltage. Based upon this comparison, the detector will output either a MARK or a SPACE. Where consecutive MARKS or SPACES are transmitted, the "transfer function" of the AM Detector will recognize that there is no relative amplitude difference between the UNKNOWN and REFERENCE voltages. The output will consequently reflect the state of the previous binary data frame.

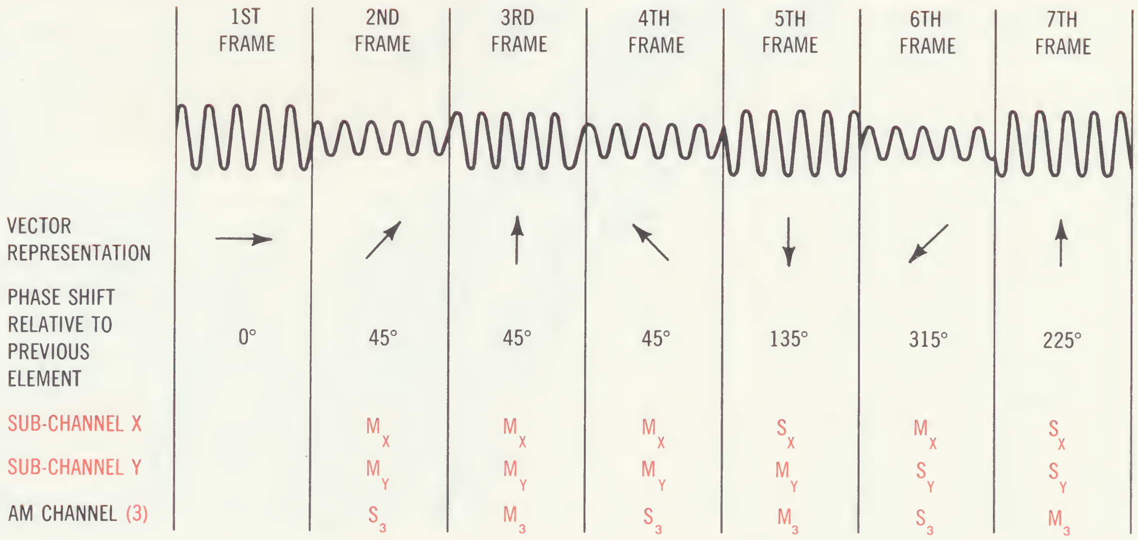


FIGURE 8 PHASE AND AMPLITUDE CODING SCHEME FOR THREE BINARY SUB-CHANNELS.

ERROR RATE VS. SIGNAL/NOISE RATIO

A comparison of different types of signalling systems is shown in Figure 9. Various forms of synchronous Phase-Shift Keyed (PSK) and synchronous Frequency-Shift Keyed (FSK) systems are considered. Also plotted are the curves for the measured Kineplex System and measured non-synchronous FSK systems. At high signal-to-noise ratio, this Kineplex System shows about 6 db improvement over the non-synchronous FSK.

The capacity of the Kineplex system is illustrated by the fact that a total information rate in excess of 5000 bits-per-second may be multiplexed in a single voice band even after allowing suitable margins for delay distortion such as would be expected on long haul land lines or HF radio systems. The signal-to-noise ratio in a 3 kc voice band required to exceed threshold (bit error rate less than 0.00001 per cent) for a signalling rate of 3000 bits-per-second is only 15 db.

Kineplex uses a simple code; narrows down the bandwidth and yet has a substantial signal-to-noise ratio gain. Modern theory teaches that we should move in exactly the opposite direction by using a complex, noise-like code and wider bands to gain in signal-to-noise ratio. This seeming paradox can be resolved when it is realized that most of the theory deals with information and coding alone. It has neglected largely the matter of detection which is in many aspects a separate subject. Improved detection is the object of Kineplex – a need which has existed for a long time and which will continue to be of vital importance with any coding scheme, however complex. It is quite proper to think of using Kineplex detection principles and going on to build a complex wideband code system when it is useful to exploit the wideband techniques. It must be remembered, however, that in many communication systems it is undesirable or impractical to think of band widening. For example, much of our useful radio spectrum is likely to remain on a narrow band basis, because of allocation considerations or because of the physical limitations imposed by nature in the form of multipath distortion.

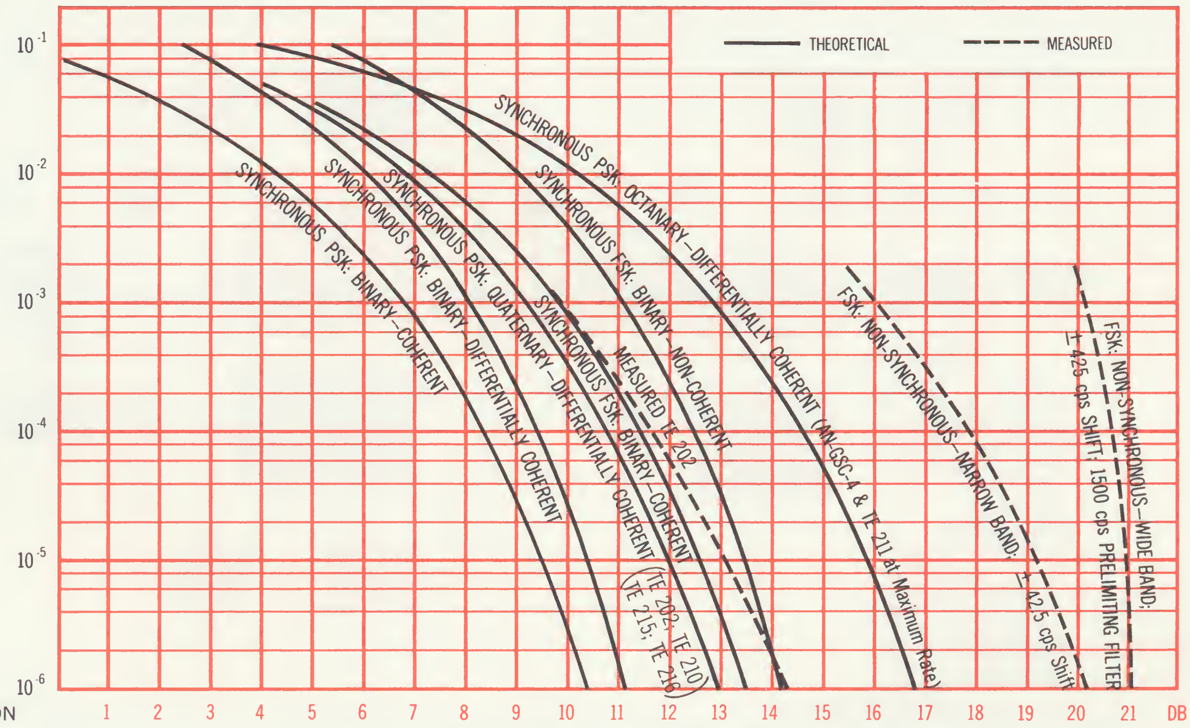


FIGURE 9 COMPARISON OF DIFFERENT TYPES OF SIGNALLING SYSTEMS.

$$\frac{E}{No} = \left(\frac{\text{ENERGY PER BIT}}{\text{NOISE POWER PER CYCLE}}\right) = \left(\frac{\text{SIGNAL POWER PER BIT PER SECOND}}{\text{NOISE POWER PER CYCLE}}\right)$$

Applications

KINEPLEX APPLICATIONS

Field experience of Collins Kineplex data transmission equipment has been extensive.

The initial operational experience included field tests carried out in 1952 and 1953 with the Air Force and Signal Corps. The tests confirmed the expected performance advantages.

In 1954, Collins began quantity production of Kineplex modem equipment for use on VHF transhorizon communication links supplied for DEW Line.

The first all solid-state Kineplex modems were developed in 1955. They provided 3000 bits-per-second transmission rates in a voice bandwidth channel. One application of this equipment was that of providing forty 100 wpm teletypewriter circuits over a voice channel.

By 1960, Collins' Kineplex operational experience included both Atlantic and Pacific transoceanic long-range HF radio circuits, VHF transhorizon circuits and VLF radio circuits, as well as all types of voice carrier systems on wireline and microwave communication systems.

This total operational experience conclusively demonstrated the high transmission speed and data accuracy advantages of Kineplex over a broad range of communications channel characteristics.

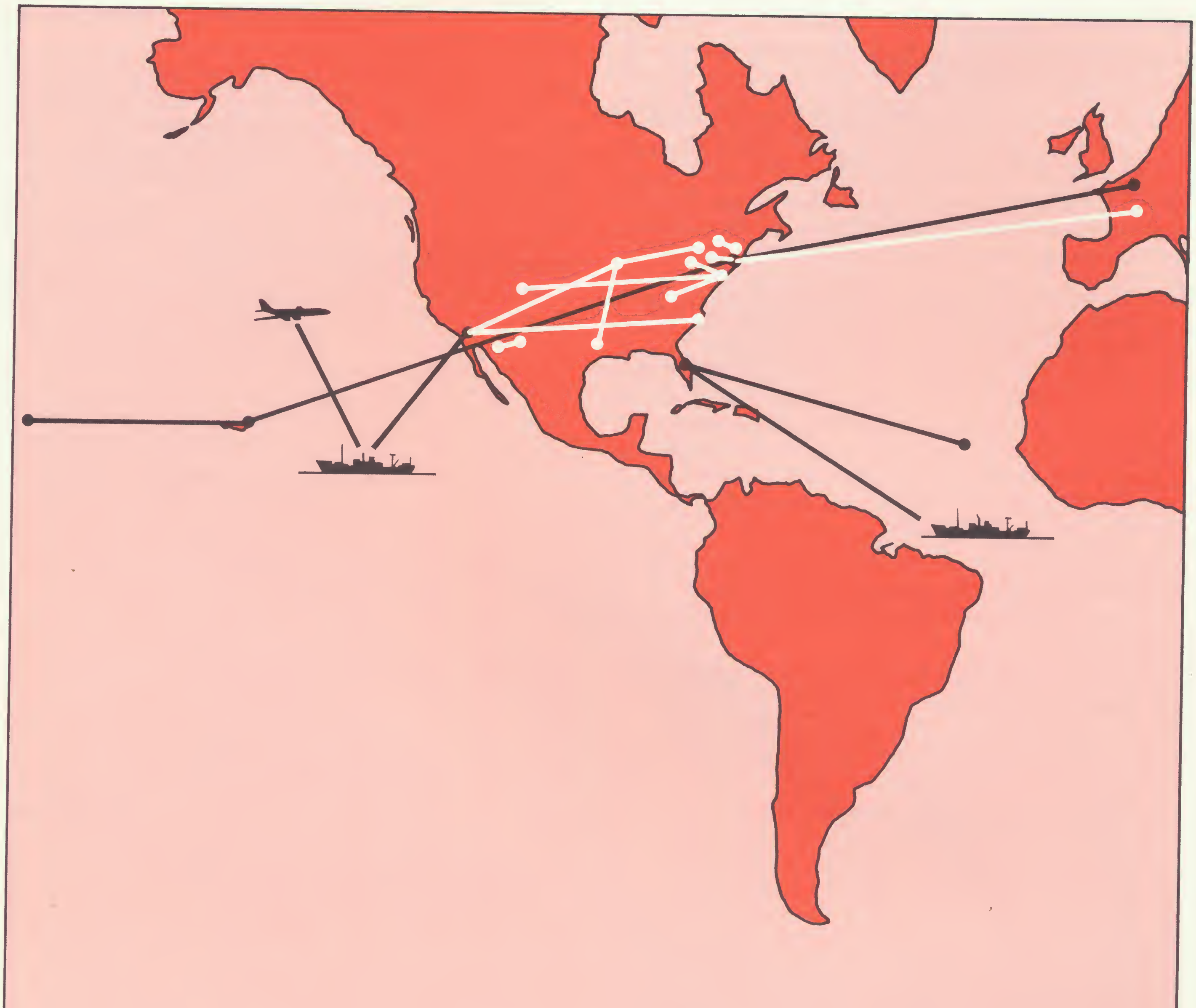
Beginning in 1960, requirements for high-speed 2400 bits-per-second data transmission service became common for a broad range of applications. Twelve hundred Kineplex high-speed, 2400 bit-per-second modems are currently in common carrier service.

Major systems that utilize Kineplex data transmission equipment are the Navy Tactical Data System, the Navy High Capacity Communication System, SAC 465L Command and Control System, DEW Line, and the Air Force Soft Talk Airborne System. The White Sands Missile Range, the Western and Eastern Test Ranges and the Pacific Missile Range, employ Kineplex modems in their communications and data handling complex. The applications involve digital transmission between radars, computers and displays; 2400 bit-per-second modems have also been used for tape-to-tape and card-to-card data transmission systems. Collins' 2400 bit-per-second modems are now used in secure digitized voice communications.

Equipment with capabilities of 4800 bits-per-second is available to transmit data between computers or from remote sources to computers.

In short, Collins modems are serving three major purposes: (1) They move large volumes of data at extremely fast speeds over short or long distances. (2) In doing so, they help in man's effort to utilize fully the awesome speed and volume capabilities of modern computers. (3) They play a critical role in defense communications.

Modems designed and built by Collins Radio Company have set industry standards for more than 15 years.



MAP SHOWING SOME OF THE KINEPLEX SYSTEMS IN OPERATION TODAY, INCLUDING COLLINS RADIO COMPANY'S OWN COMMUNICATION AND DATA SYSTEMS NETWORK. WHITE INDICATES WIRELINES, BLACK SHOWS RADIO LINKS.

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